RADIATION DETECTION AND MEASUREMENT

1. OVERVIEW

a. Quantitative measurements of radioactive contamination in the field are difficult to accomplish properly. Particles having short ranges, such as alpha and low-energy beta radiation, are significantly and incalculably affected by minute amounts of overburden; e.g., dust or precipitation. Therefore, detection rather than measurement is a more realistic goal for alpha-beta surveys. More penetrating radiations, such as gamma and higher energy X-rays, are affected less by such overburden; however, quantification of isotopes through photon emissions requires isotopic- and geometry-specific response functions.

b. Although uranium and plutonium are both alpha emitters, field survey of uranium is best accomplished by measuring beta emissions from the thorium and protactinium progeny. For plutonium, the best technique is to detect the accompanying contaminant Am-241, which emits a 60-keV gamma ray. Knowing the original assay and the age of the weapon, the ratio of plutonium to americium may be computed accurately and the total plutonium contamination determined.

c. Many of the factors that may not be controlled in a field environment may be managed in a mobile laboratory that may be brought to an accident site. Typically, the capabilities include gamma spectroscopy, low background counting for very thin alpha- and beta-emitting samples, and liquid scintillation counters for extremely low-energy beta emitters such as tritium.

2. GENERAL

a. Scope. This appendix provides detailed information on the instrumentation and associated techniques used to perform radiological monitoring at an accident involving the release of radioactive material. This appendix is not intended to serve as a “user’s manual” for the various instruments; however, it includes sufficient detail to provide an understanding of the limitations of field measurement techniques and provides for proper application and the use of techniques in an emergency. For completeness, some basic characteristics of different kinds of radiation are included. Throughout this appendix, the word “radiation” refers only to nuclear radiation found at a nuclear accident site.

b. Detection Versus Measurement.

(1) Nuclear radiation is not easy to quantify properly. Radiation detection is always a multi-step, highly indirect process. For example, in a scintillation detector, incident radiation excites a florescence material that de-excites by emitting photons of light. The light is focused onto the photocathode of a photomultiplier tube that triggers an electron avalanche. The electron shower produces an electrical pulse that activates a meter read by the operator. Not surprisingly, the quantitative relationship between the amount of radiation actually emitted and the reading on the meter is a complex function of many factors -- factors that may only be controlled within a laboratory.

(2) On the other hand, detection is the qualitative determination that radioactivity is or is not present. Although the evaluation of minimum levels of detectability is a considerable quantitative challenge for instrumentation engineers, the task of determining whether a meter records anything is considered much easier than the quantitative interpretation of that reading.

(3) The discussion in subparagraphs 2.b.(1) and 2.b.(2) suggests that the same equipment may be used for either detection or measurement. In fact, detectors usually have meters from which numbers may be extracted; however, to the extent that the user is unable to control factors that influence the readings, those readings must be recognized as indications of the presence of activity (detection) only and not measurements.

(4) In the discussions that follow in sections 3. through 7. below, personnel must be aware of the limitations imposed by field conditions and their implications on the meaning of readings taken; therefore, instructions shall carefully indicate the extent to which various instruments may be used as measurement devices or may be used only as detectors.

3. TYPES OF RADIATION

a. General. Four major forms of radiation are commonly found emanating from radioactive matter: alpha, beta, gamma, and X radiation. The marked differences in the characteristics of these radiations strongly influence their difficulty in detection and consequently, the detection methods used.

b. Alpha. An alpha particle is the heaviest and most highly charged of the common nuclear radiations. As a result, alpha particles very quickly give up their energy to any medium through which they pass, rapidly coming to equilibrium with, and disappearing in, the medium. Since nearly all common alpha radioactive contaminants emit particles of about the same energy, 5 MeV, some general statements may be made about the penetration length of alpha radiation. Generally speaking, a sheet of paper, a thin layer (a few hundredths of a millimeter) of dust, any coating of water or less than 4 cm of air are sufficient to stop alpha radiation. As a result, alpha radiation is the most difficult to detect. Moreover, since even traces of such materials are sufficient to stop some of the alpha particles and thus change detector readings, quantitative measurement of alpha radiation is impossible outside of a laboratory environment where special care may be given to sample preparation and detector efficiency.

c. Beta. Beta particles are energetic electrons emitted from the nuclei of many natural and manmade materials. Being much lighter than alpha particles, beta particles are much more penetrating. For example, a 500-keV beta particle has a range in air that is orders of magnitude longer than that of the alpha particle from plutonium, even though the latter has 10 times more energy; however, many beta-active elements emit particles with very low energies. For example, tritium emits a (maximum energy) 18.6-keV beta particle. At this low an energy, beta particles are less penetrating than common alpha particles, requiring very special techniques for detection.

d. Gamma and X Radiation. Gamma rays are a form of electromagnetic radiation and, as such, are the most penetrating of the four radiations and easiest to detect. Once emitted, gamma rays differ from X-rays only in their energies, with X-rays usually lying below a few hundred keV. As a result, X-rays are less penetrating and harder to detect; however, even a 60- keV gamma ray has a typical range of a 100 meters in air and might penetrate a centimeter of aluminum. In situations in which several kinds of radiations are present, these penetration properties make X-ray and/or gamma-ray detection the technique of choice.

e. Radiations from the Common Contaminants. Table 1., below, lists some of the commonly considered radioactive contaminants and their primary associated radiations.

Table 1. Commonly Considered Radioactive Contaminants and Their Primary Associated Radioactive Emissions

	Alpha	Beta	Photons
Am-241	X		X
H-3		X	
Pu-239	X		X
Thorium Alloys	X	X	X
U-Natural	X	X	X
U-Depleted	X	X	X
U-Highly Enriched	X	X	X

4. ALPHA DETECTION

a. Because of the extremely low penetration of alpha particles, special techniques must be used to allow the particles to enter the active region of a detector. In field instruments such as the AN/PDR-56, AN/PDR-77, and ADM-300, an extremely thin piece of aluminized Mylar® film is used on the face of the detector probe to cover a thin layer of florescent material. Energy attenuation of the incident alpha radiation by the Mylar® is estimated to be less than 10 percent; however, use of this film makes the detector extremely fragile. Thus, contact with literally any hard object, such as a blade of hard grass, may puncture the film, allowing ambient light to enter the detection region and overwhelm the photomultiplier and meter. (Even sudden temperature changes have been shown to introduce stresses that may destroy a film.) In addition, contact with a contaminated item might transfer contamination onto the detector; thus, monitoring techniques must be used that keep the detector from contacting any surface (however, recall that the range of the alpha radiation is less than 4 cm in air). This requirement to be within a few centimeters of monitored locations without ever touching one makes using such detectors impractical except for special, controlled situations (for example, monitoring individuals at the hot line or air sampler filters).

b. The sensitivity (minimum detectability) of an alpha detector is not dictated by the ability of the active region of the detector to respond to the passage of an alpha particle; counting efficiency for alpha detectors is 25 to 60 percent of the alpha particles from a distributed source that reach the detector probe. Fortunately, alpha detectors in good repair usually have a fairly low background interference. There are few counts from cosmic and other spurious radiation sources and state-of-the-art instruments easily eliminate most electronic noise. As a result, count rates in the order of a few hundred CPM are easily detectable on instruments such as the AN/PDR-77. However, the detectability is dominated by the ability of the alpha particles to get into the active region of the detector, which depends on such factors as overburden (amount of dust and/or moisture lying between the alpha emitters and the detector) and the proximity of the detector to the emitters.

c. In demonstrations conducted in the laboratory, a sealed alpha source (Am-241) was monitored with a well maintained AN/PDR-60 alpha probe and meter. Dust and water were sprinkled onto the source and changes noted. It was found that a drop of water, a heavy piece of lint, or a single thickness of tissue paper totally eliminated all readings. A light spray of water, comparable to a light dew, reduced readings by 40 to 50 percent. A layer of dust that was just visible on the shiny source had minimal effect on the count rate; however, a dust level that was only thick enough to show finger tracks reduced readings by 25 percent. These simple demonstrations reinforced the knowledge that detecting alpha particles in any but the most ideal situations is most problematic. The leaching or settling of contaminants into a grassy area or the dust stirred up by vehicular traffic on paved areas significantly decreases or eliminates alpha detection.

5. BETA AND/OR GAMMA DETECTION

a. Gamma rays and high-energy (>l MeV) beta particles are highly penetrating radiations. As a result, the major problems listed for alpha detection do not apply. Furthermore, at the energies of concern in nuclear weapon accidents, detection efficiency for most detectors is relatively high. Thus, beta and/or gamma detection is relatively easy.

b. From a detection standpoint, unfortunately, high-energy beta and gamma radiations are not the primary decay products of the most likely radioactive contaminants (for example, plutonium, uranium, or tritium). Rather, the major potential source of beta and/or gamma emitters is from fission products that might be produced in the extremely unlikely event of a partial nuclear yield. Beta and/or gamma detection, therefore, has no quantitative use in determining the extent of plutonium or uranium contamination, but is used as a safety precaution to determine any areas containing hazardous fission products.

c. Common gamma detectors are scintillation detectors (using scintillation media different from that described in section 4. above for alpha detection) or gas ionization type detectors (ion chambers, proportional counters, or GM counters). In either case, the high penetrability of the radiation allows the detector to have reasonably heavy aluminum, beryllium, or plastic windows and to be carried at a 0.5 to 1.0 m height. Dimensions of the active region of the detector (for example, the thickness of a scintillation crystal) may be made larger to increase sensitivity. Because the detection efficiencies are reasonably insensitive to energies in the energy regions of interest, the detectors may be calibrated in terms of dosage (rad or rem) rather than in terms of activity. This practice reflects the common use for beta and/or gamma detectors.

d. The Ludlum Model 3 with a Ludlum 44-9 “pancake” (GM) probe is a typical beta and/or gamma detector, but is sensitive to gamma particles. Minimum detectability for such a detector is a radiation field that produces readings two to three times greater than the background (no contaminant, natural radiation plus electronic noise) reading. All beta and/or gamma survey instruments are listed in the Radiological Monitoring Equipment page.

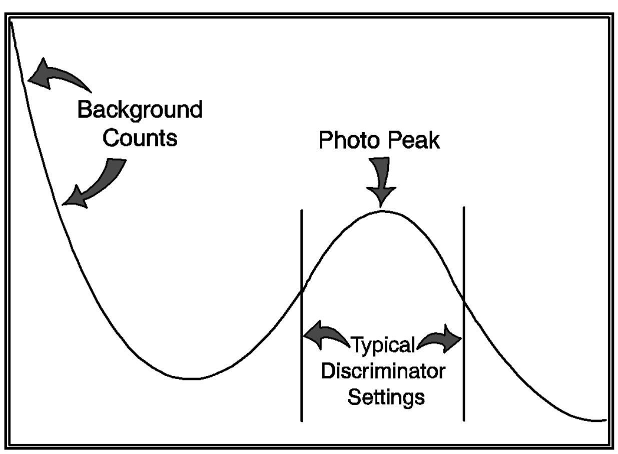
6. X-RAY DETECTION

a. For low-energy (l7 to 100-keV) X-rays, the scintillation detector is again the instrument of choice. Window thickness is again a factor, though not as much as with alpha particles. For example, the half-thickness for absorption of 17-keV X-rays in aluminum is 0.4 mm and in air is about 4m. These factors increase rapidly with energy. For 60-keV X-rays, the distances become 2.5 cm and 190m, respectively. Thus, for X-rays above 15 keV, an X-ray detector may be held at a comfortable height (0.5 m) above the contaminated surface.

b. The size of an electronic pulse produced by an X-ray in a scintillation-type detector is proportional to the energy of the X-ray. This has a most important application, commonly called pulse-height discrimination. Because of the relatively low (tens of keV) energy of the X-rays of interest, an X-ray detector and its electronics must be quite sensitive. Unfortunately, such a detector is sensitive also to the myriad radiations from natural sources and to common low-level electronic noise. The result is a deluge of signals that overwhelm the pulses from sought after X-rays. To remove the unwanted signals, circuitry is installed in the meter to ignore all pulses with sizes that lie below a user-selectable lower level (threshold). In cases of high (natural) background, it is also useful to discard all pulses with sizes greater than a user-selectable upper level. The accepted pulses, therefore, are only those from the desired X-rays and that small amount of background that happens to fall in the same pulse size region.

c. Unfortunately, pulse-height discrimination is not as "easy" as described above. In fact, the signals from the detection of identical X-rays are not identical in size; rather, a large number of such detections produce a distribution of pulse sizes that cluster about a mean pulse size. If one sets the lower-level discriminator slightly below and the upper level slightly above the mean pulse size, a large fraction of the desired pulses are eliminated, resulting in a significant decrease in detector response; however, setting the discriminator levels far from the mean admits too much background, masking the true signals (see Figure 1.). Thus, the setting of discriminator levels requires a qualitative judgment that may significantly affect the readings from a given contamination. Furthermore, since the width of the pulse size distribution depends in a most complicated way on the condition and age of the detector, it is impossible to specify one setting for all similar instruments. Rather, techniques have been developed to establish the sensitivity of a given detector, with its electronics, in a field environment. This technique is described in section 7 below.

Figure 1. Spectral Plot



d. Figure 1. shows the normal spread of pulses from a mono-energetic source mixed with a typical background spectrum and shows typical discriminator settings.

e. In spite of the complications detailed in paragraph 6.c., the scintillation detector is still the instrument of choice for detecting X-ray emitting radioactive contamination. One such detector is the FIDLER. A FIDLER (4 inches x 1 mm. NaI [T1]) probe, in good condition, mated to a Ludlum 2220 electronics package, may detect 60-keV activity as low as 0.2 $\mu Ci/m^2$. In a typical weapon grade mix for a medium-aged weapon, this mix should correspond to about 1 microcurie of plutonium per square meter. Furthermore, since the X-rays are much less affected by overburden than are alpha particles, the radiation monitor has much better control of the factors that influence its meter readings. As a result, the monitor may make quantitative measurements of the amount of radiation and infer the actual amount of contamination with far greater confidence than with any other field technique.

7. DETECTION OF URANIUM AND PLUTONIUM

a. Although uranium and plutonium are alpha emitters, they and their progeny also emit X-rays; therefore, as discussed above in section 6., the instrument of choice for detecting these elements is a scintillation detector.

b. Detecting uranium contamination is fairly straightforward. Among the radiations emitted in the decay of U-235 and its progeny is an 80-keV X-ray. The 185.7-keV X-ray is one of the most readily detectable photons from highly-enriched uranium, and has better penetrability of the entrance windows of scintillators than low-energy X-rays. Setup and field calibration of the detector, as described in this appendix, allows measurement of the X-ray activity per square meter and thus evaluation of the uranium contamination. Confidence in the accuracy of these measurements is in the 11 to 25 percent range.

c. Detecting plutonium is somewhat more complicated. Pu-239 and its progenyemit a 17-keV X-ray that may be detected with a FIDLER detector. However, absorption of that relatively low-energy X-ray by overburden plus interference by background signals in the same range as the desired X-ray make measuring the 17 keV a highly uncertain technique. Plutonium contamination may be determined more confidently through the following, indirect technique:

(1) Weapons grade plutonium contains several isotopes. In addition to the dominant Pu-239, there is always a small amount of Pu-241. Pu-241 beta decays, with a half-life of 14.35 years, to Am-241. Am-241 subsequently decays with the emission of a 60-keV X-ray which, like the 80-keV X-ray of uranium, is relatively easy to detect under field conditions. Thus, a most sensitive technique for detecting weapons grade plutonium is to detect the contaminant Am-241 and infer the accompanying plutonium.

(2) Clearly, this technique requires more information than the direct detection of radiation from the most plentiful isotope, such as knowledge of the age and original assay of the weapon material; however, decay times, weapon age, and assay are known or controllable quantities, while overburden and its effect on alpha and low-energy X-rays are not. Thus, the safeguards community has standardized on detecting plutonium through its americium progeny.

d. To ease the computations and calibration needed to measure plutonium contamination by X-ray detection in the field, the LLNL has produced a series of utility codes called the Hotspot Codes. The Hotspot HP Codes are available for all Windows platforms through XP. The Hotspot Codes include an interactive, user-friendly utility routine called FIDLER that steps a user through the process of calibrating an X-ray detector. The FIDLER code is applicable to any X-ray detector if the full calibration technique, involving a known americium calibration source, is used.

e. Particularly useful in the FIDLER code is the provision to aid in the measurement of the geometric factor for any specific detector. Measurements made at the Ballistic Research Laboratory and the LLNL have shown that the value of K(h) for h = 30 cm may vary from less than 0.4 m^2 to more than l.0 m^2, apparently depending on external configuration and subtle internal details of a particular FIDLER probe. For this reason, the FIDLER code contains both a detailed laboratory procedure and a field expedient procedure for determining K(h) for a given detector. The code also provides a default value of 0.5 m^2. This value was chosen to give a relatively conservative reading indication of contamination per count rate.

8. LABORATORY TECHNIQUES

Laboratory procedures are necessary to quantitatively measure radiation contamination. For this reason, mobile laboratories are available within the Department of Defense and the DOE/NNSA for deployment to an accident site. Although specific instrumentation shall vary, the types of laboratory analyses fall into three categories: gamma and X-ray spectroscopy, alpha-beta counting, and liquid scintillation.

a. Gamma and X-Ray Spectroscopy. The major tools involved in gamma and X-ray spectroscopy are a reasonably high-resolution gamma and/or X-ray detector (such as a High Purity Germanium or selectively high resolution NaI) and a multi-channel analyzer. With this equipment it is possible to accurately determine the energies of the gamma and X-rays emitted by a contaminated sample. Usually, spectroscopic techniques are not used for absolute measurements of amount of contamination (i.e., microcuries (μCi)) in a sample; however, by adjusting for the energy dependence of detection efficiencies and using standard spectral unfolding techniques, the relative amounts of various isotopes present in the contaminant may be determined accurately. Recalling the discussions in sections 6. through 7.h., immediate application may be seen for such information. For example, spectroscopy allows determination of the relative abundance of Am-241 to Pu-239, resulting in accurate calibration of the most sensitive (FIDLER) survey techniques.

b. Alpha and/or Beta Counting.

(1) Another laboratory technique, alpha and/or beta counting, results in a reasonably accurate determination of the absolute amount of contamination in a sample. Two types of counters are common and both are fairly simple in principle. In one, a reasonably sensitive alpha and/or beta detector, such as a thin layer of ZnS mated to a photomultiplier tube, is mounted in a chamber that is shielded to remove background radiation. A sample, made very thin to reduce self-absorption, is inserted into the chamber under the detector. In some apparatus, air is evacuated from the chamber to eliminate air absorption of the radiation. The count rate is then measured. Knowing the geometry of the experiment allows translating the count rate to an absolute evaluation of sample activity.

(2) Another alpha and/or beta technique involves gas-flow proportional counters. In these devices, a sample is inserted into the chamber of a proportional counter. Any emitted radiation causes ionization of the gas in the counter that is electronically amplified and counted.

(3) In both types of alpha and/or beta counters, the most difficult, sensitive part of the experiment is the sample preparation. To achieve absolute measurements of activity, radiation absorption must be reduced by the overburden caused by the sample itself. Techniques used include dissolving the sample onto a sample holder; evaporation of the solvent leaves a very thin, negligibly absorbing sample. Clearly, quantitative alpha and/or beta counting is a difficult, time-consuming process.

c. Liquid Scintillation.

(1) In a few cases, notably in detecting beta radiation from tritium, the energy of the radiation is so low, and the resultant absorption is so high, that solid samples may not be used for quantitative analysis. In these cases, dissolving the contaminant in a scintillating liquid may be possible. Glass vials of such liquid may then be placed in a dark chamber and the resulting scintillation light pulses counted using photomultipliers.

(2) Again, the outstanding difficulty with this process is in the sample preparation. Scintillation liquids are extremely sensitive to most impurities that tend to quench the output of light pulses. As a result, the most common technique for liquid scintillation sample gathering is to wipe a fixed area (typically 100 square centimeters) of a hard surface in the contaminated area with a small piece of filter paper. The cloth may then be immersed totally in scintillation liquid in such a way that subsequent light emission shall be visible to one of the photomultipliers in the analysis chamber. Alternatively, the filter paper may be replaced by a special plastic material that dissolves in scintillation liquid without significantly quenching light output. In either case, the technique works best when the contamination is gathered without large amounts of local dirt, oil, etc.